Scientific Goals, Objectives, Investigations, and Priorities: 2003

Mars Exploration Program Analysis Group

This document updates the goals for Mars exploration as reported in *Scientific Goals, Objectives, Investigations, and Priorities*, edited by R. Greeley and released in 2001. The original goals document has helped shape priorities for the exploration of Mars. Recent successful missions and analysis of data from them and previous missions have led to the need to update the goals and objectives of Mars exploration. The plan is to update the goals approximately every two years, corresponding to each Mars launch opportunity.

As with the 2001 version, the goals have been revised with extensive participation from the community of scientists and engineers active in Mars exploration. The MEPAG Chair and steering committee appointed a subcommittee of the Mars Exploration Program Analysis Group (MEPAG). The committee consisted of the following individuals representing the four major goals identified in the 2001 report:

G. Jeffrey Taylor, University of Hawai‘i, Chair
Andrew Morrison, Jet Propulsion Laboratory, support
David Beaty, Jet Propulsion Laboratory, ex officio
Search for Life:
Dawn Sumner, University of California, Davis
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Climate:
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Glenn MacPherson, Smithsonian Institution
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Human Exploration:
John Connolly, Johnson Space Center
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The goals committee met through weekly teleconferences from mid-January 2003 leading up to the MEPAG meeting held February 26-27, 2003, in Tempe, Arizona. The committee identified important potential revisions during this time period and outlined a series of issues to discuss at the Tempe MEPAG meeting. Over 100 Mars experts, in addition to program managers, attended (see Appendix A). Goals revisions were discussed in four breakout groups, corresponding to the four major goals for Mars exploration. A primary objective of the meeting was to identify central issues and questions to discuss with the entire Mars exploration community through a online survey that was managed and co-sponsored by the Geophysical Laboratory of the Carnegie Institution of Washington. Over 300 individuals participated in the survey. A draft report was then circulated via e-mail to the Mars Community and discussed in detail during the September 10-11 MEPAG meeting in Pasadena, California. Over 150 scientists attended the Pasadena meeting, in addition to program managers. Thus, the updated goals outlined here represent the consensus view of a broad cross section of the Mars exploration community.

The four goals described below are ***not*** listed in priority order. Each is important and they are interrelated. All must be pursued aggressively to understand the entire complex Mars system and how it operated through time. We hope this report will be useful in identifying cross-cutting themes among the four goals. Nevertheless, within each goal, we list objectives and investigations in priority order. The online survey was particularly useful in establishing these priorities. No attempt was made to weight the priorities, but it is clear that the highest priority objective or investigation is not ten times—in most cases not even two times—more important than the lowest one. A future online addendum will include descriptions of the types of measurements needed to conduct each investigation. It will not include specific measurement requirements. The consensus view is that such detailed requirements ought to be defined by Science Definition Teams and Payload Science Integration Groups for program missions and by the Science Teams for Scout missions. Subsequent reviews will determine if those requirements are appropriate for a specific mission.

As noted in the first MEPAG goals report, completion of all the investigations will require decades of effort. Many investigations may never be truly complete (even if they have a high priority). Thus, evaluations of missions should be based on how well the investigations are addressed. While priorities should influence the sequence in which the investigations are conducted, they should not necessarily be done serially, as many other factors come into play in the overall Mars Program. On the other hand, we have tried to identify cases where one investigation should be done before another. In such cases, the investigation that should be done first was given a higher priority, even if in the long run the second investigation will be more important. We also include assessments of where we need technology development to conduct the investigations. In Goal I, this is discussed very extensively because of recent developments in analytical techniques.

Even a cursory reading of the goals, objectives, and investigations outlined below will show that we need to develop several crucial capabilities. The most important of these are: (1) *Access to all of Mars*--high and low latitudes, rough and smooth surfaces, low and high elevations. (2) *Access to the subsurface*, from a meter to hundreds of meters, through a combination of drilling and geophysical sounding. (3) *Access to time varying phenomena*; hence we need to be able to make some measurements over a long period of time (at least a year). This applies particularly to climate studies. (4) *Access to microscopic scales* by instruments capable of measuring chemical and isotopic compositions and to determine mineralogy and the nature of mineral intergrowths. Many of the measurements described can be done by orbiting instruments or landed packages, but others absolutely require that we return samples from Mars. There is a strong consensus on the need for sample return missions. As noted in other MEPAG reports, study of samples collected from known locations on Mars and from sites whose geological context has been determined from remote sensing measurements has the potential to revolutionize our view of Mars.

I. GOAL: DETERMINE IF LIFE EVER AROSE ON MARS

Three essential approaches to determining if life ever arose on Mars are searching for extant life, searching for evidence of ancient life, and characterizing the distribution and fluxes of biologically essential elements. These overarching scientific questions can be addressed simultaneously, as each requires basic knowledge of the distributions of water and carbon on Mars and an understanding of the processes influencing their cycling in the context of Martian environments. The critical scientific objectives for evaluating if life ever arose on Mars can be summarized under the following headings: A) Identify Habitable Environments, B) Characterize Carbon Cycling in its Geochemical Context, and C) Search for Life. Identification of habitable environments directs the locations and approaches for investigating the distribution of carbon on Mars and searching for biomarkers. The goals that have been identified are expected to overlap as shown in Figure 1.

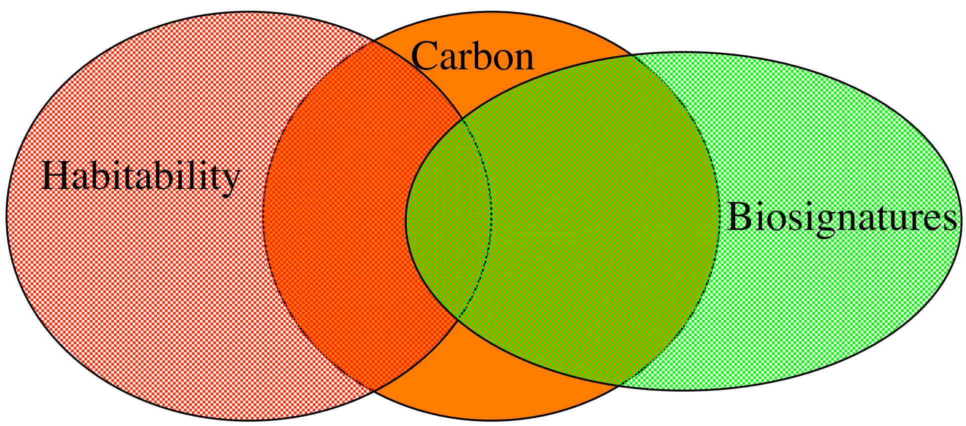

Figure 1. The expected overlap of the 3 objectives of Identify Habitable Environments, B) Characterize Carbon Cycling in its Geochemical Context, and C) Search for Life.

Technological advances are leading to advanced concepts for instruments capable of making *in situ* measurements with high sensitivities and low detection limits. We outline some of these in section D. To spur development of flight technology there must also be an increase in terrestrial groundtruth tests for instrumentation on samples of relevance to Mars exploration. This aids the development of instrumentation while ensuring that the detection limits are appropriately low. The astrobiology community should decide on a suite of highly characterized samples from relevant environments, and these samples should be curated for the testing of developing instrumentation.

Each of the following objectives contains a range of investigations that are placed in a priority order. The first investigation in each objective has been deemed to be of greater importance to the second, and each primary investigation is of greater than the secondary investigation in each objective, i.e. A1>B1>C1>A2>B2 etc. Below the second to third level investigations, priority rankings among the objectives have not been established, and the quality of proposed measurements is the best basis on which to decide the importance of pursuing each investigation.

A. Objective: Identify Habitable Environments

One of the challenges of determining if life ever arose on Mars is identifying places where it may presently occur or where the record of its past existence may be preserved. A "follow the water" strategy provides the best first-order approach for identifying habitable environments, not only because water is an essential requirement for life, but also because its identification and mapping (particularly in the subsurface, where most of Mars' water is thought to reside) can be pursued on a global, regional and local basis using established geophysical and other remote sensing techniques. This approach can also be used to identify other essential components of a habitable environment, including the key elements that provide the raw materials to build cells and provide the necessary sources of energy to support life.

1. Investigation: Establish the current distribution of water in all its forms on Mars.

Water on Mars is thought to be present in a variety of forms and potential distributions, ranging from trace amounts of vapor in the atmosphere to substantial reservoirs of liquid, ice and hydrous minerals that may be present in the subsurface. The presence of abundant water is supported by the existence of the Martian perennial polar caps, the geomorphic evidence of present day ground ice and past fluvial discharges, and by the Mars Odyssey GRS detection of abundant hydrogen (as water ice and/or hydrous minerals) within the upper meter of the surface. To assist the search for past or present life, the identity of the highest priority H_2O targets, and the depth and geographic distribution of their most accessible occurrences, must be known with sufficient precision to guide the placement of subsequent investigations by deep drills and other types of robotic platforms. To understand the conditions that gave rise to these potential habitats it is also desirable to characterize their geologic and climatic context. The highest priority H_2O targets for the identification of potential habitats are: (1) liquid water -- which may be present in as pockets of brine in the near-subsurface, in association with geothermally active regions (such as Tharsis and Elysium), as super-cooled thin films within the lower cryosphere, and beneath the cryosphere as confined, unconfined and perched aquifers; (2) massive ground ice – which may preserve evidence of former life and exist in a complex stratigraphy beneath the northern plains and the floors of Hellas, Argyre, and Valles Marineris, an expectation based on the possible former existence of a Noachian ocean, and the geomorphic evidence for extensive and repeated flooding by Hesperian-age outflow channel activity; and (3) the polar layered deposits – whose strata may preserve evidence of climatically-responsive biological activity (at the poles and elsewhere on the planet) and whose ice-rich environment may result in episodic and persistent occurrences of liquid water associated with climate change, local geothermal activity and the presence of basal lakes.

2. Investigation: Identify and characterize deposits affected by hydrological processes.

Deposits influenced by hydrological processes provide protected habitats for extant life and the best repositories for preserving a fossil record of Martian life. Minerals that precipitate from water can encase biological signatures, thereby increasing their preservation potential, and the geometry of sediments can reflect biological processes, in addition to providing data on geochemical cycles.

3. Investigation: Identify and characterize phases containing C, H, O, N, P and S, including minerals, ices, and gases, and the fluxes of these elements between phases.

Carbon is the building block of life, and detailed investigations for carbon are the primary focus of Objective B. Nitrogen, phosphorous and sulfur are critical elements for life, and the phases containing these elements and fluxes of these elements can reflect biological processes and the availability of these elements for life. They are often intimately associated with carbon and their distribution is commonly controlled by water and oxidation states, so interpreting these elemental cycles in terms of C, H, and O is extremely valuable to the search for life.

4. Investigation: Determine the array of potential energy sources available on Mars to sustain biological processes.

Biological systems require energy. The availability of potential energy sources is a critical component of habitability, and understanding how life might use them is a critical component of designing scientifically robust life detection experiments. Sources of energy may include chemical redox, pH gradients, geothermal heat, radioactivity, incident radiation (sunlight), atmospheric processes, etc.

B. Objective: Characterize Carbon Cycling in its Geochemical Context

Carbon is the building block of life on Earth and is probably the building block of life on Mars (if life exists/existed). Understanding how carbon has been distributed on Mars through time, including now, is critical for understanding where to look for life on Mars, how life might have evolved on Mars, and how life might have originated on Mars. In addition, there may be aspects of the carbon cycle that reveal the presence of life, and results are likely to strongly influence approaches to searching for definitive biosignatures. Thus, characterization of the carbon cycle is critical to determining if life ever arose on Mars.

Understanding the origin of organic carbon is particularly important and sources on Mars could be from several reservoirs that are summarized in Table 1. One of the most significant difficulties in characterizing organic carbon is constraining the source of that organic carbon. Terrestrial contamination is a significant concern, because of the need to avoid false identification of organic carbon or specific organic molecules on Mars. In addition, meteoritic delivery of organic carbon to the surface of Mars and abiotic organic synthesis processes could produce measurable organic carbon concentrations. Understanding the origin of organic carbon is as important as identifying it.

We assume that extraterrestrial life would be based on carbon chemistry, which may be an oversimplification. However, this assumption must be the starting point in the search for extraterrestrial life. If anomalous measurements indicate the presence of non-carbon based macromolecules associated with some form of life-like processes then further experiments can be designed to address this problem.

Table 1. Sources of Organic carbon that need to be detected/deconvolved from each other on Mars.

Source of Carbon	Carbon compounds/comments
Prebiotic/protobiotic molecules from meteoritic / cometary influx	Amino acids, purines and pyrimidines, polycyclic aromatic hydrocarbons, chain hydrocarbons, fatty acids, sugars and sugar derivatives.
Prebiotic/protobiotic molecules from abiotic process on Mars	Amino acids, purines and pyrimidines, polycyclic aromatic hydrocarbons, chain hydrocarbons, fatty acids, sugars and sugar derivatives.
Terrestrial contaminating organics	Condensation products derived from rocket exhaust, lubricants, plasticizers, atmospheric contaminants
Terrestrial contaminating organisms	Whole cells, cell components (LPS, DNA, proteins, cytochromes)
Terrestrial like organisms – from earth	Organisms not present on the craft measuring them, but had been previously transferred from Earth by either meteorite impact or contamination of previous space craft. Target molecules could include individual genes, membrane constituents, specific enzymes, and co-enzymes that would be expected to be over expressed or adapted in Martian conditions.
Terrestrial-like organisms – evolved on Mars	Organisms that utilize terrestrial like biochemistries and have evolved on Mars Target molecules could include individual genes, membrane constituents, specific enzymes, and co-enzymes that would be expected to be over expressed or adapted in Martian conditions.
Non-terrestrial-like organisms	Utilizes an array of molecules for information storage, information transfer, compartmentalization and enzymatic activity that differ from those used by extant terrestrial life. An example would be the use of novel amino acids or nucleotides
Fossil biomarkers	Detection of established terrestrial fossil biomarkers such as hopanes, archaeal lipids and steranes, for the detection of the diagenetic remains of terrestrial based life.

1. Investigation: Determine the distribution and composition of organic carbon on Mars.

The distribution and composition of organic carbon have not been characterized, but are instrumental in directing the search for life. (Methane and other simple reduced carbon molecules are included as "organic carbon" in this context.) Abiotic synthesis of organics, delivery of organics to Mars via meteorites, and possible biological production of organics must all be evaluated in the context of carbon cycling on Mars. Characterizing the molecular and isotopic composition of organic carbon is essential for determining the origin of the organics shown in Table 1, which includes the types of organic materials that need to be detected and deconvolved from each other. Investigations require sufficient spacecraft cleaning and verification to avoid likelihood of contamination, in addition to careful planning of specific methods to identify and exclude forward contamination at the experiment level. Example measurements include analysis of the concentration and isotopic composition of organic carbon, characterization of the molecular structure of organic carbon, or identifying and monitoring reduced carbon (e.g. methane) fluxes.

<u>2. Investigation:</u> Characterize the distribution and composition of inorganic carbon reservoirs on Mars through time.

Transformations of carbon between inorganic and organic carbon reservoirs are a characteristic of life. Evaluating carbon reservoirs and the fluxes among them is critical to understanding both the modern and geological evolution of carbon availability, and the inorganic carbon reservoirs are an important link in the cycle. The distribution of these reservoirs can also reveal critical habitability information because they can record climate records. Example measurements include searching for carbonate minerals from orbit, *in situ*, or in returned samples, characterizingCO2 fluxes on various time scales either globally or locally, or measuring the isotopic composition of any inorganic reservoir.

<u>3. Investigation:</u> Characterize Links Between C and H, O, N, P, and S

The carbon cycle in intimately linked to H, O, N, P, and S, particularly in the presence of life. Identifying connections among the geological cycles of these elements will substantially aid interpretations of the carbon cycle and may provide indicators that can be used to narrow the search for life to high probability sites. Example measurements include mineralogical characterization of samples containing C, N, P, or S, isotopic or oxidation state characterization of S-containing phases, or identification of reactions involving any of these elements.

<u>4. Investigation:</u> Oxidation chemistry of the near surface through time.

The surface of Mars is oxidizing, but the composition and properties of this oxidant are unknown. Characterizing the reactivity of the near surface of Mars, including atmospheric (e.g. electrical discharges) and radiation processes as well as chemical processes with depth in the regolith and within weathered rocks is critical to interpreting the paucity or possible absence of organic carbon on the surface of Mars. Understanding the oxidation chemistry and the processes controlling its variations will aid in interpreting measurements of organic carbon and help direct the search for life if no organics are found on the surface. Example measurements include identifying species and concentrations of oxidants, characterizing the processes forming and destroying them, or characterizing concentrations and fluxes of redox sensitive gases in the lower atmosphere.

C. Objective: Search for Life

The search for life of Mars is a scientifically exciting and challenging endeavor. The following investigations look for biosignatures, which are defined as results that REQUIRE the presence or past presence of life. Commonly, multiple observations in a context are required to identify biosignatures, and multiple scales of observation are very important. Four investigations currently recognized as biosignatures are listed here. Investigation 1: Characterize complex organics, is the highest priority. Investigation 1 and some measurement to address Investigation 4 require sufficient spacecraft cleaning and verification to avoid likelihood of contamination, in addition to careful planning of specific methods to identify and exclude forward contamination at the experiment level. Investigations 2 and 3, which depend on the spatial distribution of signatures, are less sensitive to contamination and may be more practical to pursue first. Remote sensing techniques addressing investigation 4 also have much lower to no contamination issues.

A fifth investigation concept consists of suites of observations based on searches for correlations in biological indicators, which independently suggest life and only in combination can provide a true biosignature. Such investigations would consist of characterizing systems that are strongly suggestive of life based on previous results. Use of suites of observations that are designed to provide several lines of indicative evidence would be used to evaluate a testable hypothesis focused on known sites of interest from previous observations. Many of these combinations have not yet been identified, and it is expected that exciting proposals for suites of observations will be seriously considered in choosing investigations to search for life.

<u>1. Investigation:</u> Characterize complex organics, looking for those that require biology

The identification of complex organics that can only be produced biologically is a very strong biosignature, provided that forward contamination by terrestrial organics can be excluded. Measurements for this investigation must include appropriate methods to identify and exclude forward contamination as a source of the target materials. Example measurements may include characterization of organics such as DNA, nucleotides, chlorophyll, etc. for extant life; hopanes, steranes, isoprenoids, etc. for fossil life; or cumulative properties of organics such as homochirality.

<u>2. Investigation</u>: Characterize the spatial distribution of chemical and/or isotopic signatures, looking for those that are inconsistent with abiotic systems

The spatial distribution of chemical or isotopic variations can be a biosignature, if the distribution is inconsistent with abiotic processes. Example measurements may include imaging of the distribution of organics on a surface or in minerals; identifying correlations among isotopic values and elemental concentrations that reflect biological processes; or the presence of reduced and oxidized gas phases in disequilibrium.

<u>3. Investigation:</u> Characterize the morphology or morphological distribution of mineralogical signatures, looking for those that are inconsistent with abiotic systems.

Sedimentary and weathered rocks can preserve biosignatures in the distribution of grains and minerals or in the morphology of biologically produced minerals. Example measurements may include micron to nanometer imaging of crystals or morphological characterization of sedimentary lamination.

<u>4. Investigation:</u> Identify temporal chemical variations requiring life

Extant life may be active, producing observable temporal changes in chemistry over time scales of a lander experiment to years. Monitoring systems that may harbor life is an excellent way to identify the presence of life if possible abiotic reactions are thoroughly understood and forward contamination can be identified or excluded. It is critical that measurements capable of being contaminated include appropriate methods to identify and exclude forward contamination as a source of the signatures being monitored. Example measurements may include monitoring the flux of gases thought to be biologically produced; monitoring oxidative changes in a way that excludes abiotic reactions; or performing experiments to look for metabolic processes.

D. Technology Development (no priority order)

Contamination minimization and monitoring

Whether for sample return issues or planetary protection, technologies for the minimization and monitoring of contamination passed by the platform and instruments to the surface of Mars and vice versa would help interpret the results from life detection measurements made either in-situ or on returned samples. The instigation of "point of source monitoring" technology for microbial and organic contamination is extremely important. As are investigations on the types and sources of space craft contamination, there containment, the threat to instrument measurements posed by these sources, effects of minimal sterilization and cleaning of critical equipment on planetary protection.

Sample acquisition

The detection of suitable samples from in-situ platforms for both analysis and sample return is critical. Suites of analytical instrumentation are dependent on delivery of appropriate samples for analysis and therefore the further development of instruments and methodologies for suitable sample identification are crucial. This selection is one that starts in orbit and moves to the submicron scale. Technology that allows increased sensitivity of orbital instruments for the definition of suitable landing spots both by morphology and chemistry should continue. Techniques to identify suitable morphological, and spectral details that could identify a site of interest should be studied and where possible integrated with remote operations, to locate that sample.

Sample handling

Once a suitable site has been identified and a sample acquired and traveled to the next pressing issue is one of handling that sample. If the sample is above robotic drilling (into a rock), manipulation and analysis should be conducted. Whether the sample is to be interrogated by contact / down bore hole instrumentation or brought within the platform for analysis by an instrument suite, methods to ensure sample integrity (i.e. reduction of contamination from platform, reduction of cross contamination from past samples, phase changes etc) should be further developed. These instruments would greatly benefit from the emerging technology outlined above.

Sample extraction

For many analytical instruments extraction of suitable molecules for analysis is essential. Whether the instrument contains a dedicated unit for this purpose or a standard interface for instrument suites is proposed. Technologies and instrument suite definition should have in mind sample extraction needs during development. Certain packages may require instruments with two or more extraction requirements (e.g., dry verses wet samples).

Sample return

The rewards of returning a sample are huge in terms of the science questions that can be answered compared to in situ robotic measurements. Specific technologies designed to facilitate the return of samples must be addressed and include all the issues raised in section D plus specific problems in returning to earth with a sample intact.

Miniaturization

With the emphasis on techniques that can supply mutually supportive data, miniaturization of instruments would allow a greater number as well as in some cases more sensitive instruments to be available for selection into instrument suites. Specific technologies that have emerged are microelectronic machines (MEMS), microfluidics, and nanotechnology. The implications and difficulties of space flight instrument development need to be communicated to groups exploring these technologies for further development. Furthermore new technologies in the area of platform (whether fixed or roving) design and miniaturization of key lander and rover components must continue.

Software development

Software for autonomous space craft automation should be further developed. This is crucial for the operations of a platform on Mars, sample acquisition and go-to technology, sample handling, data interpretation (image recognition algorithms), autonomous selection and deployment of instruments available from an instrument suite.

II. GOAL: UNDERSTANDING THE PROCESSES AND HISTORY OF CLIMATE ON MARS

The fundamental scientific questions which underlie this goal are how has the climate of Mars evolved over time to reach its current state, and what processes have operated to produce this evolution. These extremely important scientific questions are in accord with several key science objectives found in the NASA Solar System Exploration Roadmap [2003]. Mars climate can be defined as the mean state and variability of its atmosphere and exchangeable volatile reservoirs (near the surface) evaluated from diurnal to geologic time scales. An understanding of Mars climatic evolution rests upon gaining a full understanding of the fundamental processes governing its climate system, and thus upon obtaining detailed observations of the current (observable) system. Goal II also is in line with the recent recommendation of the Solar System Exploration Survey [2002] which calls out the clear need for Mars upper atmosphere measurements in order to properly characterize current volatile escape rates. Objectives A and B below are considered equally important for targeted study at Mars, since it is clear that the entire Mars atmosphere is a highly coupled system. Objective C focuses upon specific investigations that will measure key indicators of the past climate of Mars. Finally, Objective D is added in order to highlight mission critical atmospheric measurements that will reduce risk and enhance overall science return, benefiting all future missions to the planet. No attempt has been made to prioritize these risk mitigation and engineering related measurements since all are important.

A. Objective: Characterize Mars' Lower Atmosphere Present Climate and Climate Processes (investigations in priority order)

1. **<u>Investigation:</u> Determine the processes controlling the present distributions of water, carbon dioxide, and dust.**

Understanding the factors that control the annual variations of volatiles and dust is necessary to determine to what extent today's processes have controlled climate change in the past. Requires continuing global mapping (not necessarily with a single mission) and landed observations on daily and seasonal timescales. Measurements of lower atmosphere processes should be made whenever possible on all spacecraft bound for the lower atmosphere.

2. **<u>Investigation</u>: Determine inter-annual variability and long-term trends in the present climate.**

This determination will test to what degree the Martian climate is changing today. Requires extending the measurements of investigation 1 to multiple years, and decadal monitoring of key atmospheric variables.

3. <u>Investigation:</u> Search for micro-climates.

Detection of exceptionally or recently wet or warm locales and areas of significant change in surface accumulations of volatiles or dust would identify sites for *in situ* exploration. Requires global search for sites based on topography or changes in volatile distributions and surface properties (e.g., temperature or albedo). Requires for local warm spots and concentrations of water vapor.

4. <u>Investigation:</u> Determine the production/loss, reaction rates, and global distributions of key photochemical species (O_3, H_2O_2, CO, OH, etc.) and their interaction with surface materials.

Surface sinks and sources and lower atmospheric distributions are required to interpret atmospheric escape rates and upper atmosphere aeronomy. Current photochemical models predict a missing sink for HOx that may be dust or cloud or unknown chemistry. There is also considerable uncertainty over surface fluxes of major species.

B. Objective: Characterize Mars' Upper Atmosphere Present Climate and Climate Processes (investigations in priority order)

<u>1. Investigation</u>: Determine the rates of escape of key species from the Martian atmosphere, their correlation with seasonal and solar variability, their modification by remnant crustal magnetic fields, and their connection with lower atmosphere phenomenon (e.g., dust storms).

These provide crucial constraints to atmospheric evolution models that extrapolate these rates to determine past climates. Requires global orbiter observations of neutral and plasma species, temperatures, and winds in the upper atmosphere, and the systematic monitoring of these atmospheric fields over multiple Mars years to capture inter-annual variability induced by the solar cycle, seasons, and dust storms. It also requires more thorough and higher-resolution measurements of crustal magnetic fields.

2. **<u>Investigation:</u> Determine the short and long term trends (daily, seasonal and solar cycle) in the upper atmosphere climate (thermosphere, ionosphere and exosphere).**

This will improve both our fundamental understanding of atmospheres and our engineering ability for aerobraking and aerocapture maneuvers. Requires measurements yielding the mean state and variability of the neutral and plasma environments from continuing spacecraft aerobraking campaigns and other observations over multiple Mars years.

3. Objective : Characterize Mars' Ancient Climate and Climate Processes for the Lower and Upper Atmospheres (investigations in priority order)

1. **<u>Investigation:</u> Determine the stable isotopic, noble gas, and trace gas composition of the present-day bulk atmosphere.**

These provide quantitative constraints on the evolution of atmospheric composition and on the source and sinks of the major gas inventories. Requires high-precision isotopic measurements of the atmosphere.

2. <u>Investigation:</u> Find physical and chemical records of past climates.

These provide the basis for understanding the extent and timing (e.g., gradual change or abrupt transition) of past climates on Mars. Requires: determining sedimentary stratigraphy and the distribution of aqueous weathering products.

3. <u>Investigation:</u> Characterize the stratigraphic record of climate change at polar layered deposits and residual ice caps.

The polar regions suggest repeated geologically recent climate change. A key to understanding their histories is to determine the relative ages of polar layering and volatile reservoirs. Requires detailed imaging and measurements of volatile concentrations and isotopic compositions, and their variations.

D. Objective: Characterize the State and Processes of the Martian Atmosphere of Critical Importance for the Safe Operation of Spacecraft (no priority order).

Atmospheric processes of importance for the safe implementation of spacecraft missions are addressed in this objective. These investigations will yield the critical information necessary to improve the likelihood of successful execution of missions in the Martian environment. Investigations seek to characterize the atmosphere from the surface to 400 km altitude to support spacecraft navigation and operation, including landing, flight, aerocapture, aerobraking, long-term orbital stability, targeting of observations from orbit, and mission planning. Every effort should be made to accommodate instruments that address these investigations on each spacecraft bound for Mars.

1. **<u>Investigation:</u> Understand the thermal and dynamical behavior of the planetary boundary layer.**

The lowest portion (<5km) of the atmosphere can be highly turbulent. Horizontal and vertical winds in this region represent a significant risk to spacecraft Entry, Descent, and Landing (EDL) and the operation of aerial platforms (balloons and aeroplanes). The turbulence also transports heat, and as such is a concern for thermal design. The turbulence is driven by thermal contrasts between the surface and the atmosphere, and mechanical interactions between the mean wind and the rough planetary surface. This investigation is designed to probe the connections between surface temperature, the modification of surface and air temperatures by aerosol radiative heating, and the dynamical and thermal state of the lower atmosphere.

2. **<u>Investigation:</u> Understand and monitor the behavior of the lower atmosphere (0-80km) on synoptic scales.**

Mars exhibits significant seasonal and dramatic, episodic changes in the state of the atmosphere. Of great concern to the operation of surface and near-surface spacecraft, and for aerobraking, aerocapture, or aeropass maneuvers, is the onset of regional and global dust storms. The mechanisms of storm development are unknown at this time, and thus cannot be predicted with current models. Prediction will require much further study of these events, while mitigation is greatly assisted by their early observation. It is critical for support of Mars missions that continuously-operational, meteorological assets be maintained in Martian orbit.

3. **<u>Investigation:</u> Determine the atmospheric mass density and its variation over the 80 to 200 km altitude range.**

Aerobraking. aerocapture, and aeropass operations use the atmosphere as a brake. These operations are safest when the drag imparted by the atmosphere can be accurately estimated ahead of time. Unfortunately, the Martian atmosphere exhibits substantial variations in density at a given geometric height due to the influence of the diurnal cycle, seasonal cycle, large-scale atmospheric circulation, and the propagation of waves. Mapping and understanding the processes responsible for the density variations in the upper atmosphere is critical to high-precision spacecraft trajectory planning. For example, techniques for measuring and predicting the mass density on time scales of hours to days are key requirements for aerobraking. This information is also important for mission planning (e.g., estimating the amount of fuel needed throughout mission life).

4. **<u>Investigation:</u> Determine the atmospheric mass density and its variations at altitudes above 200 km.**

This range is important for precision targeting of observations and for long-term orbital stability.

III. GOAL: DETERMINE THE EVOLUTION OF THE SURFACE AND INTERIOR OF MARS

Insight into the composition, structure, and history of Mars is fundamental to understanding the solar system as a whole, as well as providing insight into the history and processes of our own planet. Thus there are compelling scientific motivations for the study of the surface and interior of the planet in its own right. The recent heightened interest in the possibility of life on Mars provides additional emphasis for these investigations. Geology informs virtually every aspect of the study of conditions conducive to the origin and persistence of life, and the study of the interior provides important clues about a wide range of topics, including the early history of Mars, sources of volatiles and geothermal energy.

The unique aspect of Mars which in many ways make it appear more Earth-like and sets it apart from the other planets is the presence and activity of liquid water at or near the surface. This has enormous geological implications affecting, for example, erosion, weathering, heat flow, and the possibility of life (which can, in turn, have significant effects on geological processes). Thus an emphasis on water is a logical framework within which to explore the planet.

There are several overarching principles that should guide any planning for addressing the objectives described below. Virtually all these investigations will eventually require landing on the surface for in-situ measurements or collection of samples for return to Earth. Although resources will always be limited, it should be recognized that the success in reaching our objectives will be compromised unless we are able to access the appropriate locations for carrying out the measurements. In particular, systems must be developed which will allow:

- Global accessibility. As we learn more about Mars and begin to ascertain the best locations for furthering our investigations, we must be able to land and carry out these investigations over as wide a range of locations (e.g., latitude, elevation) and settings (e.g., surface slopes/roughness, season) as possible.
- Depth accessibility. Many of these investigations require subsurface access in order to address fundamental questions. These requirements range from less than a meter to hundreds of meters; some can be addressed through geophysical sounding.
- "Nano-accessibility". In order to derive meaningful results, many of the most important analytical measurements must be made at extremely small scales. This will require considerable technology development for in-situ instrumentation and, in many cases, the return of samples to the Earth.

Finally, the importance of returning samples to the Earth for detailed and exhaustive laboratory analysis cannot be too strongly emphasized. Over the past two decades virtually every scientific group which has considered the course of Mars exploration, including MEPAG, has consistently ratified the firm consensus of the scientific community that the return of material from Mars has a uniquely rich potential to revolutionize our understanding across a broad range of disciplines.

A. Objective: Determine the nature and evolution of the geologic processes that have created and modified the Martian crust and surface (investigations in priority order)

1. **<u>Investigation</u>: Determine the present state, 3-dimensional distribution, and cycling of water on Mars.**

Water is an important geologic material on Mars, influencing most geological processes including the formation of sedimentary, igneous and metamorphic rocks, the weathering of geological materials, and deformation of the lithosphere. Requires global observations using subsurface sounding and remote sensing, coupled with detailed local and regional sounding and measurements.

2. **<u>Investigation</u>: Evaluate fluvial, subaqueous, and subaerial sedimentary processes and their evolution through time, up to and including the present.**

Fluvial and lacustrine sediments are likely sites to detect traces of prebiotic compounds and evidence of life. Sediments also record the history of water processes on Mars. Polar layered terrains in particular may preserve a unique record of climate history. Eolian sediments record a combination of globally-averaged and locally-derived fine-grained sediments and weathering products. Sedimentary layers are also likely sites of past or present aquifers. Requires knowledge of the age, sequence, lithology, and composition of sedimentary rocks (including chemical deposits), the rates, durations, environmental conditions, and mechanics of weathering, cementation, and transport processes, and the fluvial and lacustrine record preserved in the morphology of the surface and near-subsurface.

3. **<u>Investigation:</u> Calibrate the cratering record and absolute ages for Mars.**

The evolution of the surface, interior, and surface of Mars, as well as the possible evolution of life, must be placed in an absolute timescale, which is presently lacking for Mars. Requires absolute ages of geological units of known crater ages.

4. **<u>Investigation</u>: Evaluate igneous processes and their evolution through time, including the present**.

This study the broad range of igneous processes including, for example, volcanic outgassing and volatile evolution. In addition to dramatically molding the surface of the planet, volcanic processes are the primary mechanism for release of water and atmospheric gasses that support potential past and present life and human exploration. Sites of present day volcanism, if any, may be prime sites for the search for life. Requires global imaging, geologic mapping, techniques for distinguishing igneous and sedimentary rocks, evaluation of current activity.

5. **<u>Investigation:</u> Characterize surface-atmosphere interactions on Mars, including polar, eolian, chemical, weathering, and mass-wasting processes.**

The focus of this investigation is on processes that have operated for the last million years as recorded in the upper 1 m to 1 km of Mars. Understanding present geologic, hydrologic, and atmospheric processes is the key to understanding past environments and possible locations for near-surface water. Knowing the chemistry and mineralogy of both near surface rocks and alteration products is essential for calibrating remote sensing data. This study also has strong implications for resources and hazards for future human exploration. Requires orbital remote sensing of surface and subsurface, and direct measurements of sediments and atmospheric boundary layer processes.

6. <u>Investigation</u>: Determine the large-scale vertical structure and chemical and mineralogical composition of the crust and its regional variations. This includes, for example, the structure and origin of hemispheric dichotomy.

The vertical and global variation of rock properties and composition record formative events in the planet's early history, place constraints on the distribution of subsurface aquifers, and aid interpretation of past igneous and sedimentary processes. Requires global and local remote sensing and subsurface sounding, detailed geologic mapping, and determination of mineralogy and composition of surface material.

7. <u>Investigation</u>: Document the tectonic history of the Martian crust, including present activity.

Understanding the tectonic record is crucial for understanding the geologic history as well as the temporal evolution of internal processes. This, in turn, places constraints on release of volatiles from differentiation and volcanic activity and the effect of tectonic structures (faults and fractures in particular) on subsurface hydrology. Requires geologic mapping using global topographic data combined with high-resolution images, magnetic and gravity data, and seismic monitoring.

8. <u>Investigation:</u> Evaluate the distribution and intensity of hydrothermal processes through time, up to and including the present.

Hydrothermal systems are thought to be the connected with the earliest evolution of life on the Earth. Hydrothermal systems may also play an important role in the chemical and isotopic evolution of the atmosphere, and the formation of the Martian soil. Deposits from hydrothermal systems have the potential to record the history of the biosphere and crust-atmosphere interactions throughout Martian history. Requires knowledge of the age and duration of the hydrothermal system, the heat source, and the isotopic and trace element chemistry and mineralogy of the materials deposited.

9. <u>Investigation</u>: Determine the processes of regolith formation and subsequent modification, including weathering and diagenetic processes.

The regolith is a filter through which we view most of the Martian surface by remote sensing. In addition, it may provide a valuable record of the history of surface conditions and processes.

Requires quantitative measurement of mineralogy, chemistry, and physical parameters of the surface and near-subsurface.

10. Investigation: Determine the nature of crustal magnetization and its origin.
The magnetization of the Martian crust is poorly understood, but is intimately related to the igneous, thermal, tectonic and hydrologic history of the crust. Requires high-resolution mapping of the magnetic field and knowledge of the mineralogy and magnetization of the surface.

11. Investigation: Evaluate the effect of impacts on the evolution of the Martian crust.
Impact is arguably the most important of the processes shaping the crust and surface of Mars. A firm understanding of effects of impacts on the structural, topographic and thermal history is a prerequisite for any broad understanding of the Martian crust and surface. Requires geologic mapping using global topographic data combined with high-resolution images and remote sensing.

B. Objective: Characterize the structure, composition, dynamics, and evolution of Mars' interior (investigations in priority order)

1. Investigation: Characterize the structure and dynamics of Mars' interior.
Understanding the structure and dynamical processes of the deep interior is fundamental for understanding the origin and evolution of Mars in general and its surface evolution and the release of water and atmospheric gasses in particular. For example, the thickness of the crust and the size of the core provide strong constraints on the bulk composition of the planet and the manner in which it differentiated. Requires mineralogic, isotopic, seismic, magnetic, gravity and heat flow data bearing directly and indirectly on interior structure and processes.

2. Investigation: Determine the origin and history of the magnetic field.
Evidence that Mars had a magnetic field early in its history has important implications for its formation and early evolution, as well as for the retention of its early atmosphere and for the shielding of the surface from incoming radiation and the possible evolution of life. Requires high-precision, high-resolution global, regional, and local magnetic measurements, as well as mineralogic, isotopic, seismic, gravity and heat flow data bearing on interior structure and processes.

3. Investigation: Determine the chemical and thermal evolution of the planet.
Knowledge of the chemical and thermal evolution places constraints on the composition, quantity, and rate of release of volatiles (water and atmospheric gasses) to the surface. Requires measurements of the internal structure, thermal state, surface composition and mineralogy, and geologic relationships.

4. **<u>Investigation:</u> Study the structure, dynamics and composition of Phobos and Deimos as indicators of the formation and early evolution of Mars.**

Dynamical arguments suggest that the origin of Phobos and Deimos are intimately connected with that of Mars itself. The dynamics of their orbits may provide constraints on the structure of Mars' interior and their composition may provide further clues to its evolution.

GOAL IV: PREPARE FOR HUMAN EXPLORATION

Robotic missions serve as logical precursors to eventual human exploration of space. In the same way that the Lunar Orbiters, Ranger and Surveyor landers paved the way for the Apollo moon landings, a series of robotic robotic Mars Exploration Program missions is charting the course for future human exploration of Mars. Goal IV of the MEPAG document differs from the previous Goals in that it addresses science questions specific to increasing the safety, decreasing the cost, and increasing the productivity of human crews on Mars. To address these issues this section describes both the data sets that are to be collected (Objective A), and the demonstrations of critical technologies that must be validated in the actual Martian environment (Objective B).

A. Objective: Acquire Martian environmental data sets (listed in priority order)

Scientist-astronauts on the Martian surface will add a new dimension of discovery and exploration to a Mars science program. The safety and productivity of these human explorers requires an understanding of the hazards present in the Martian environment, and the design of systems to mitigate them. Quantitative models of the Martian atmosphere, surface, and subsurface will increase the safety of human missions, and help to identify resources that may greatly decrease the cost of human exploration.

1. **<u>Investigation</u>: Determine the ionizing radiation environment at the Martian surface and the shielding properties of the Martian soil and atmosphere.**

The propagation of high energy particles through the Martian atmosphere must be understood, and the measurement of secondary particles must be made at the surface to determine the buffering (or amplifying) effects of the Martian atmosphere, to understand the backscatter effects of the regolith, and to validate radiation transport models for the Martian atmosphere. Simultaneous monitoring of the ionizing radiation from Mars' orbit and at the surface to determine the shielding component of the atmosphere is desirable. Soil and dust from the Martian surface offer a readily available source of shielding material. The properties of the soil that contribute to its shielding effectiveness must be quantified to establish the transport of high-energy particles. UV is also a source of ionizing radiation and knowledge of the UV spectrum at the surface is required.

2. **<u>Investigation:</u> Determine the chemical and toxicological properties of Martian surface materials.**

Measurements related to toxicity and reactivity are needed to develop hazard mitigation strategies to ensure the safety of human explorers on the Martian surface. Surface materials include all soil, dust, ice, water or atmospheric aerosols that human explorers may come in contact with. Measurements require *in-situ* surface and subsurface sample analysis or return of environmentally preserved samples if *in-situ* measurement is not possible. Multiple sites should be sampled including designated human missions sites.

3. <u>**Investigation:**</u> **Measure atmospheric parameters and variations that affect atmospheric flight and surface systems.**

Upper level atmospheric parameters play a critical role in planning safe entry, descent, and landings for human missions. Knowledge of near-surface (boundary layer) properties is needed for safe design and operation of human surface systems.

4. <u>**Investigation:**</u> **Understand the characteristics, accessibility, and distribution of water resources in regolith, and Martian groundwater systems.**

Water is a principal resource to humans, and a critical element in surface operations. Measurements require geophysical investigations and *in-situ* sample analysis.

5. <u>**Investigation:**</u> **Measure the engineering properties of the Martian surface, and characterize topography, and other environment characteristics of candidate outpost sites.**

Soil and surface engineering data are needed to eliminate uncertainty in the design of landers, mobile systems, EVA suits and tools, and power and thermal systems. Also, site certification for human outposts requires a set of data about the specific site that can best be performed by surface investigations. Measurements require *in-situ* analysis at individual, specific sites.

6. <u>**Investigation:**</u> **Determine electrical effects in the atmosphere**.

Mixing dust and sand of various compositions and sizes has the potential to develop electric charge, and in "dust devils" and dust storms to create large electric fields. Electrostatic charging and associated electrical discharges pose possible hazards to surface operations through unanticipated arcing, dust adhesion, and radio frequency (RF) contamination (charge grain/antenna incidence). These effects become particularly significant in a low pressure (low Paschen breakdown) atmosphere.

B. Objective: Conduct in-situ engineering science demonstrations (listed in priority order)

Technology validation and engineering science demonstrations are needed to reduce the risk inherent in new, unproven technologies. Demonstrating the performance of these technologies in the Martian environment prior to their use on human flights will reduce risk and improve confidence in mission safety. The investigations listed in this section were chosen because of their high degree of interaction with the Martian environment, and because of the uncertainty of whether analog testing would supply sufficient data to reduce risk and cost, or increase performance of these systems.

1. <u>**Investigation:**</u> **Demonstrate terminal phase hazard avoidance and precision landing.**

System testing is necessary to decrease the risks associated with soft landing, and to enable pinpoint landing. Validation requires flight demonstration during terminal descent phase.

2. **Investigation:** **Demonstrate mid-range lift-to-drag (mid-L/D) aeroentry /aerocapture vehicle flight.**
Mid-L/D (0.4-0.8) aeroentry shapes will be required as payload masses increase. Mid-L/D aeroassist increases landed vehicle payload performance and landing precision. Validation requires flight demonstration during aeroentry phase of the mission. Flight validation must be performed with a vehicle size that yields test results scalable to vehicle performance for a human mission.

3. **Investigation:** **Demonstrate high-Mach deployable aerodecelerator performance.**
Higher ballistic coefficient entry vehicles will result from flying more massive landers. This will result in higher parachute deployment speeds, that are beyond the qualification of current parachute systems. Validation requires flight demonstration during Mars entry phase.

4. **Investigation:** **Demonstrate in-situ propellant (methane, oxygen) production (ISPP) and in-situ consumables production (ISCP) (fuel cell reagents, oxygen, water, buffer gasses).**
The potential for Martian resources to be converted to useable products needs to be evaluated. Components that directly interact with the Martian environment should be evaluated in a relevant environment to determine their performance. End-to-end performance may be evaluated by acquisition of local resources, processing, storage, and potential use of end products. Validation requires process verification with experiments performed *in-situ* to reduce both engineering design uncertainties and the program risk of incorporating this technology into future robotic/human missions.

5. **Investigation:** **Demonstrate in-situ water collection and conditioning using surface resources.**
Water concentrations in the Mars surface regolith, and concepts to collect and separate the water, should be evaluated in a relevant environment to determine their performance. Hardware and investigation objectives can be performed separately or combined and integrated with other regolith characterization experiments. Validation requires process verification with *in-situ* experiments to reduce both engineering design uncertainties and the program risk of incorporating this technology into future robotic/human missions.

6. **Investigation**: **Demonstrate access to subsurface resources.**
The Martian subsurface contains potential resources (e.g., water) as well as potentially important scientific samples. Drilling or other techniques for accessing the subsurface need to be developed. Validation requires *in-situ* demonstration.

7. **Investigation:** **Demonstrate plant growth in the Martian environment.**
Demonstrate the ability of the Martian environment (soil, solar flux, radiation, etc.) to support life, such as plant growth, to support future human missions. Validation requires *in-situ* measurements and process verification.